Special Contribution
Numerical Wind Tunnel: History and Evolution of Supercomputing

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1. Introduction

Some of the readers may be familiar with the term "numerical wind tunnel," also known as a "digital wind tunnel." An Internet search of these terms will usually lead to a supercomputer system, such as the "Numerical Wind Tunnel System" deployed at the National Aerospace Laboratory of Japan (NAL). This is a laboratory operated under the former Science and Technology Agency, before it was integrated into the Japan Aerospace Exploration Agency (JAXA). The first supercomputer-based numerical wind tunnel was introduced in 1993. It became the world's most outstanding computing system as first-generation parallel vector supercomputers, making it to the pinnacle of the TOP500 list (http://www.top500.org) and garnering the Gordon Bell Prize. While the numerical wind tunnel is thus closely associated with supercomputers, what we discuss in this article is not the numerical wind tunnel as such, but the system in a broader sense of its practicality, concepts, purposes, and achievements.

The numerical wind tunnel was first conceived in the 1980s, and thus it has existed for about 30 years. During this period, what challenges has it addressed, and how successful has it been in overcoming them so far? Have we realized the objectives set forth initially? Has there been progress made in other aspects, such as applications and deployment?

This article addresses these questions, drawing on the numerical wind tunnel project pursued at the JAXA Chofu Aerospace Center, focusing on its historical context, current status, and future prospects, especially in connection with high-performance computing (HPC).

2. The roots of numerical wind tunnel

To understand the numerical wind tunnel, we need first to give some background accounts regarding a "wind tunnel." JAXA describes a wind tunnel as an experimental facility used "to investigate aerodynamic characteristics (aerodynamics) and flow phenomena of the air surrounding aircraft or spacecraft. Airflow around aircraft can be simulated in a wind tunnel, which generates actual airflow artificially around an airframe model installed within the wind tunnel. By measuring some properties such as aerodynamic forces and pressure distributions around the model air frame, the wind tunnel allows us to grasp air behavior accurately."1)

The model mentioned here is not at all like those fragile replicas one would imagine to see in a display cabinet. It must be a stiff model carved out of a metal block and so on, because it must endure tremendous force in high-speed wind tunnel testing. Fabricating the model is a costly and time-consuming process as it also requires high-precision work (**Figure 1**). Using a large-scale facility for testing requires dedicated specialist operators, and the test gives rise to a high energy cost. Therefore, the tests involving a wind tunnel (wind tunnel testing) are generally expensive. Moreover, test conditions must be carefully considered and adjusted in order to obtain data on aerodynamic force and other parameters. However, once the test is ready to be executed, it proves to be remarkably efficient in terms of data productivity. For instance, it is possible to obtain approximately 200 cases of data per day where one case represents a combination of Mach number and elevation angle. These are the characteristics of wind

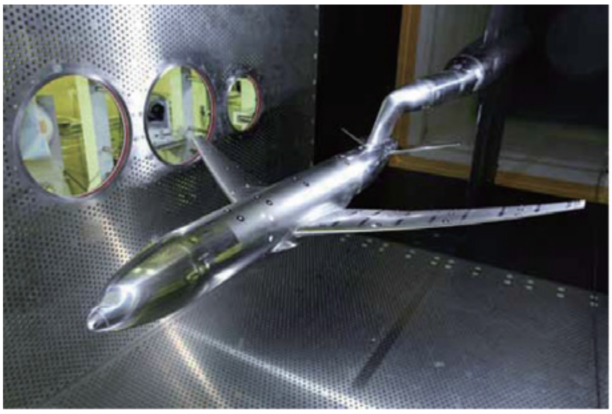


Figure 1
Example of wind tunnel model.

tunnel testing. Given the above, the concepts of aerodynamic models, artificial generation of actual airflow, and measurement of aerodynamic forces and/or pressure distributions, represent some keywords to describe wind tunnel testing. To view this from the opposite direction, it means that simulating a wind tunnel would be possible if these factors were reproduced by other means. The idea of realizing this through computing is the origin of the concept of a numerical wind tunnel.

Hajime Miyoshi and Susumu Takanashi of NAL are attributed with possibly being the first engineers who revealed the concept of a numerical wind tunnel to the public. Miyoshi described a numerical wind tunnel in his 1986 paper,[2)] saying that "the numerical wind tunnel substitutes high-speed computers and employs numerical simulation technology to replace the wind tunnel testing" and "in the numerical wind tunnel testing, the space surrounding the aircraft model was divided into grids ... and the obtained difference equation system is computed, in other words, it numerically simulates the wind tunnel testing. By this method, a flow field is calculated, and used to estimate the aerodynamic characteristics of the actual aircraft." Miyoshi is particularly enthusiastic about realizing a supercomputer-based numerical wind tunnel, pointing out the value of supercomputers to be recognized, given the fact that a lot of time is spent on wind tunnel testing in aircraft development, and significant improvements have been made to computational capacity.

Meanwhile, Takanashi depicted a numerical wind tunnel in his 1987 article[3)] in terms of a system comprising a computer and software. Notably, he predicted the role the numerical wind tunnel would play in our time quite accurately, as he states that "the numerical wind tunnel primarily complements wind tunnel testing, or is used as an alternative design tool by converting conditions for shapes and flows into parameters to estimate the aerodynamics," "however, it is at least certain that a large part of wind tunnel testing will be replaced by numerical simulations, and eventually the wind tunnel testing will be primarily used to verify the simulation results."

3. Historical background to numerical wind tunnel

In 1987, NAL introduced Fujitsu's vector supercomputer FACOM VP400. With a processing capacity of 1.1 GFLOPS (giga floating-point operations per second), it represented the dawn of the full-blown numerical simulation era. Thus, the system as a whole was called the numerical simulator (NS) or numerical simulator system (NSS), and this first version was called NS1 (or NSS1).

It was also the early days of the development of computational fluid dynamics (CFD) codes. There were the LANS3D[4)] developed by Fujii and Obayashi, and the multiblock Euler code by Sawada.[5)] They were applied in 3D viscous flow analysis of wings or a wing/fuselage combination, and inviscid flow field of an entire aircraft. These achievements were significant in the sense that they demonstrated the potential of the supercomputer-based numerical analysis to actual forms for the first time in the world.

In 1993, NAL introduced a supercomputer-aided numerical wind tunnel as a core system of the second-generation numerical simulator, NS2.[6)] This system was named NWT, standing for Numerical Wind Tunnel. The NWT was initially equipped with 140 nodes (236 GFLOPS; later increased to 166 nodes, 280 GFLOPS), with a crossbar network, forming a distributed-memory parallel vector supercomputer system. The NWT made a variety of analyses possible. It was applied to solve actual problems such as those related to the unsteady flow through blade rows in a jet engine[7)] and the real gas flow around an atmospheric reentry vehicle.[8)] It was also applied in investigations into physical phenomena, realizing detailed analyses of a homogeneous isotropic turbulence and a lifted flame.[9)]

However, the system could not conduct an analysis of actual wind tunnel testing. There are three reasons for this. First, the system's computational capacity was too small to process the data taken from a real wind tunnel. Analyzing the viscous flow around a wind tunnel model mounted on the sting (a supporting fixture) would require more than 10 million grid points, which far exceeded the NWT's performance of 280 GFLOPS. Apart from the processing performance, there were other obstacles such as insufficient CPU memory capacity and disk space. Thus, the system could only show the computational possibility, but it was not sufficient to be put to practical applications.

Second, the software was insufficient not only for the code development but for pre-processing (grid generation) and post-processing (visualization) as well. Since computers can only handle digital data, computational points must be defined within a space appropriately, which requires a process of grid generation. In those days, the only solver available for analysis was a structured grid solver, which involved grids with regularly distributed grid points. It needed a very long time to generate structured grids. It took several months in some cases, even with specialist systems engineers involved. Technologies were not advanced enough to deal with complex, real-life geometries.

The third reason is that there were insufficient data to verify the simulation results. While a simulation may yield some results, quantitative comparison is only possible by using wind tunnel test results as a reference point. This was also an issue concerning the availability of wind tunnel test data. It was also difficult to validate the turbulence and other physical models.

To make a numerical wind tunnel practically useful, computational performance must be improved above all. That is, the first issue must be overcome. As a successor of the NWT, NAL introduced Fujitsu's UNIX server, PRIMEPOWER HPC2500 scalar system in 2002 as its third-generation NS3.6) HPC2500 was configured with 32 CPUs per node (SMP: symmetric multiprocessing), with a node performance of 64 GFLOPS; it had 56 nodes in total, and a performance of 9.3 TFLOPS. With 3.6 TBytes of memory and 620 TBytes disk space, it had sufficient specifications for the purpose of a numerical wind tunnel for the first time.

On the software front, multiblock structured grids were becoming the mainstream in viscous flow analysis of the era, and UPACS10) was the code often employed. The Message Passing Interface (MPI) became prevalent, and it was compatible with the concept of parallel computing using multiblock grids. This NS3 system and the multiblock code made it possible to analyze the model in a wind tunnel for the first time.11) However, the multiblock grids also involved the generation of a grid, which required expert skill and long lead time. In terms of the computational speed, also, it did not come even close to the data productivity of wind tunnel testing.

In 2003, NAL was integrated into JAXA, together with the Institute of Space and Astronautical Science and the National Space Development Agency of Japan. In 2009, JAXA installed a new supercomputer system, and named it differently from its predecessors' NS acronym, calling it JAXA Supercomputer System, or JSS. The first version was thus called JSS1. The core system of the JSS1 was also known as JSS-M system, a cluster system with Fujitsu's high-end technical computing server FX1 as nodes, integrated through a fat tree network.12) The FX1 as a node had a node performance of 40 GFLOPS and 32 GBytes of memory. The M system as a whole had 3,008 nodes, delivering a performance of 120 TFLOPS. In the FX1 node, 1 socket was comprised of 4 core CPUs, and the typical memory bandwidth was 40 GBytes/second (Byte/Flop ratio of 1).

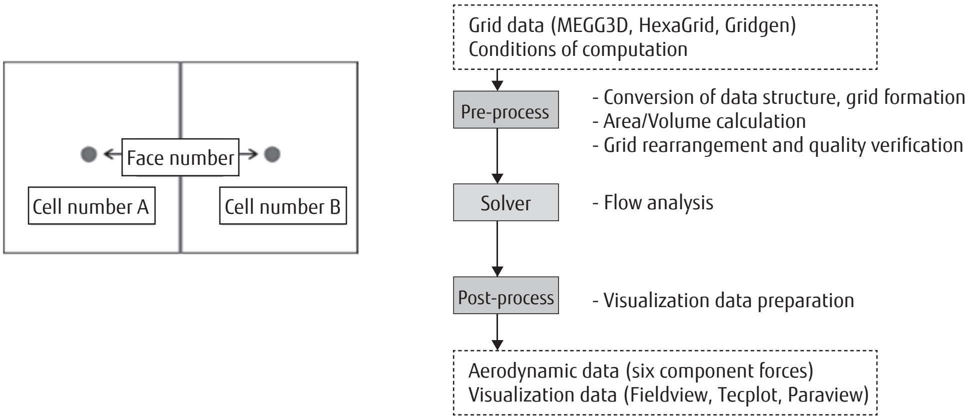
As for a CFD solver, the trend moved from a structured grid solver to an unstructured grid one (e.g., TAS Code)13) during the time of the previous system. With unstructured grids, the burden of generating grids was significantly reduced as the process did not require grid points to be aligned. However, CFD solvers and computers must bear the burden instead. The unstructured solver tends to compromise performance (i.e., slows down the computation speed) if grids are generated without careful consideration, as it increases instances of recursive memory access. As the system accesses the memory randomly, the computer must have a high-performing memory.

In order to address these challenges, we developed from scratch a high-speed unstructured grid flow solver, Fast Aerodynamic Routines (FaSTAR).14) FaSTAR adopted a simple data structure as shown in **Figure 2**: (a) it stored only the index data list to reference from face numbers to cell numbers, and the data were rearranged during the preconditioning to reduce cache misses. Furthermore, it adopted an implicit scheme and a multigrid method to accelerate convergence; (b) the computing process was sectionalized to reduce the load borne by the solver kernel.

Meanwhile, the FX1 node was suitable for the unstructured grid solver as it was capable of high performance, as the Byte/Flop ratio of 1 indicates. As a result, helped with convergence acceleration offered by the multigrid method, FaSTAR realized a fast convergence of 40 minutes to conduct an analysis of a complete aircraft involving 10 million grid points, using 25 FX1 nodes (100-core), as shown in **Figure 3**.[15] It took under 1 hour to complete the convergence, and the computation speed thus achieved was the world's fastest class of the era.[16]

In 2008, a new program was initiated, namely, "Digital/Analog Hybrid Wind Tunnel Project." It aimed to reciprocally complement the shortcomings of experimental fluid dynamics (EFD), such as the wind tunnel testing and CFD, and facilitate synergistic value-creation from a combination of the two.[17]

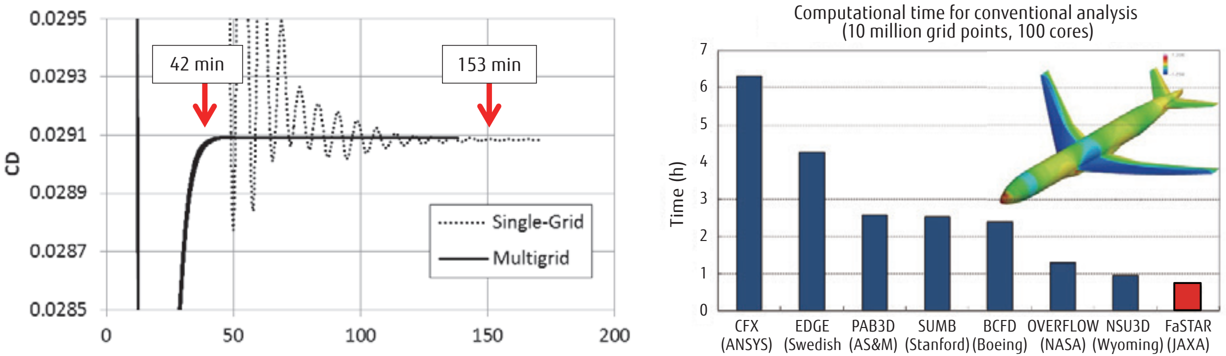
Since the unstructured grid replaced the structured grid method as the mainstream of flow solvers, grid generation became much less burdensome. Nevertheless, the time required for generating grids and the quality of the task execution still posed a significant challenge. Against this background, a breakthrough came with the development of an automatic grid generation tool,



(a) Data structure

(b) Analytical process

Figure 2
Unstructured grid solver FaSTAR.



CD: Drag coefficient

(a) Acceleration of convergence with multigrid method

(b) Comparison of time required for convergence among CFD codes

Figure 3
Convergence performance of FaSTAR with FX1.

called HexaGrid.[18) In principle, this uses orthogonal hexahedra to fill the space, and generates layered grids near the wall surface to resolve thin boundary layers. An orthogonal hexahedron may be inferior in terms of geometrical adaptivity, but the orthogonality is suited for automatization and speed enhancement, with little numerical error. Thus, it became possible to generate a grid within an hour, something that would normally take more than one month with conventional methods. The HexaGrid thus made significant contributions not only to the data-productivity of the numerical wind tunnel, but also in terms of the aforementioned second challenge, in combination with FaSTAR.

Another major reason why we became involved in the development of the hybrid wind tunnel was that we expected to gain great insights from wind tunnel testing. Through the tasks of developing the hybrid wind tunnel, we understood much about wind tunnel testing in terms of the characteristics of tasks, ways of taking the data and their corrections, and also the errors (uncertainty) involved. This helped us to make quantitative improvements to the numerical analysis results. That is, it helped us greatly to overcome the aforementioned third challenge.

Table 1 shows the results of wind tunnel testing on the linear region of aircraft aerodynamic performance, in terms of lift, drag and pitching moment coefficients, together with the error margin (uncertainty, impact) in CFD analyses.19) The table indicates that the error margin (uncertainty) is almost equal between the wind tunnel testing and CFD simulation if the ultimate answer we seek is aircraft aerodynamics at flight. These results show that CFD is almost as useful as wind tunnel testing to obtain aircraft aerodynamic data. However, the data acquired through wind tunnel testing are indispensable for validating the physical model used in CFD. In commercial aircraft development, the error margin of drag must be within 1% to evaluate the aircraft's fuel efficiency. Considering this, improving the measurement precision in wind tunnel testing and accumulating detailed data for CFD validation are important tasks to be accomplished.

4. Numerical wind tunnel at present and challenges

JAXA introduced its second-generation supercomputer system, JSS2, in 2015. Its core system, SORA-MA, employs a cluster system using Fujitsu Supercomputer, PRIMEHPC FX100 for nodes, and it is connected through a dedicated network, TOFU2. The system comprises a total of 3,240 nodes, realizing a performance of 3.49 PFLOPS in 2016.20)

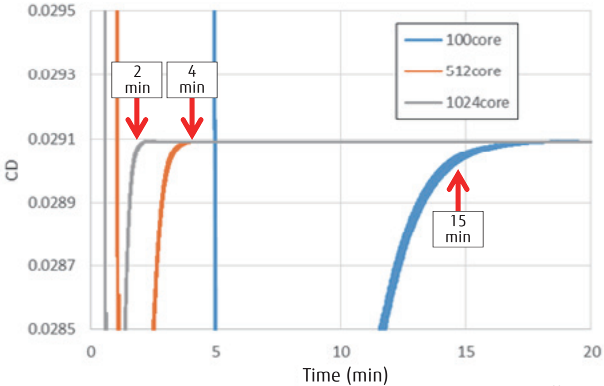
While we had achieved a computing time of 40 minutes per case with the JSS1 system (10 million grid points, 100 cores, 25 nodes), we needed to make a twenty-fold improvement over the JSS1 to reach the data-production rate of wind tunnel testing i.e., 200 cases per day, requiring us to realize the speed of a few minutes per case. The core performance of the JSS2 was almost three times that of the JSS1. This meant that, on a 100-core configuration like the JSS1, the data could be processed in approximately 15 minutes, one-third of the time required for the JSS1 (**Figure 4**).21) Using the same grids, the processing was further reduced to 2 minutes on a 1,000-core configuration. Given the 2-minute-per-case performance efficiency, it is theoretically possible to handle 30 cases per hour. Thus, operating the system for 8 hours a day, it can

Table 1
Comparison of the error margin (uncertainty) factors.

	C_L	C_D	C_m
Near-field support interference (straight sting)	−1%	−4%	−10%
Near-field support interference (blade)	−1%	−1%	−1%
Far-field support interference	−1%	−6%	−5%
Transition	2%	−2%	4%
Model deformation	−5%	−4%	−7%
Wall interference	−1%	1%	0%
Grid	4%	5%	10%
Turbulence model	4%	5%	7%

realize a computational capacity of 240 cases a day. At this point, the numerical wind tunnel possibly reached the data-productivity of wind tunnel testing. It could be further enhanced by running several jobs simultaneously, making it possible to surpass the productivity of its counterpart easily. However, the development of an aircraft needs a database with several hundred thousand cases of aerodynamic data under varying parameters.[22] At the pace of 240 cases a day, it would still require many days to obtain this amount of data. Thus, CFD has still further to go in terms of enhancing the computational speed.

While the data productivity has been elevated to the level of wind tunnel testing, there are still other challenges. One of the major issues is the scope of the CFD application. Presently, CFD can only command a simulation fairly accurately with cruise flight condition, but for other conditions such as when flow separation occurs, the accuracy deteriorates. In **Figure 5 (a)**, an aircraft flight envelop is presented. The x-axis represents the flight speed while the y-axis is for weight coefficient (or the lift, where the weight coefficient in cruising is 1G). The present CFD can reliably analyze the area in the vicinity of the cruise conditions, as indicated in the center of the diagram. However, the accuracy is compromised on the edge of the envelop due to flow separation and buffet-induced vibration. In these domains, conventional steady simulation is not adequate, and instead large-scale unsteady simulation is needed [**Figure 5 (b)**].

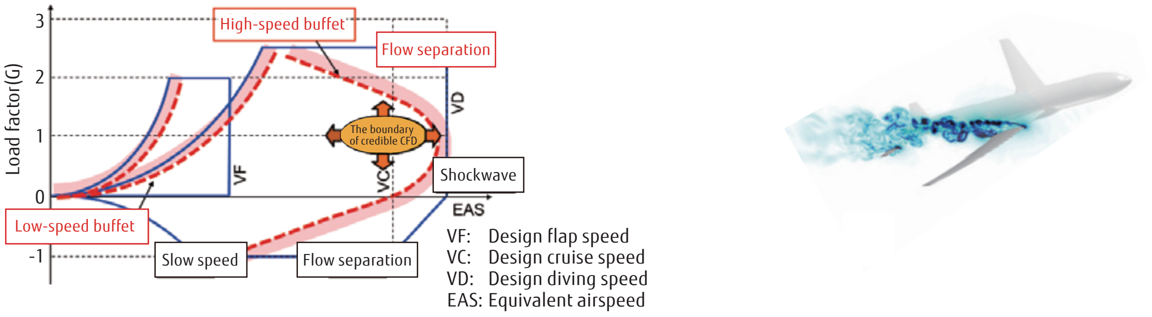


CD: Drag coefficient

Figure 4
Convergence performance of FaSTAR with FX100.

5. Future development of numerical wind tunnel

Figure 6 depicts JAXA supercomputer's performance and major numerical analyses conducted during the approximately 30 years covering JAXA systems from the NS1 to JSS2. The performance of JAXA supercomputers has increased to 3 million times during this period. In the meantime, CFD and other numerical analysis methods have also made progress, going from simple geometry to complex geometry, from single discipline (mainly fluid dynamics) to multi disciplines (coupled analysis), from mere suggestion of potential to actual practical application, and from mere analyses to the application to design assistance and optimization. We call this development the spiral structure of performance enhancement and application development for supercomputers. The development of the numerical wind tunnel as described above, in one sense, represents this spiral seen from the viewpoint of the wind tunnel facility. Although the performance



VF: Design flap speed
VC: Design cruise speed
VD: Design diving speed
EAS: Equivalent airspeed

(a) Aircraft flight envelope

(b) Buffet analysis at a large attack angle

Figure 5
Challenges for numerical wind tunnel.

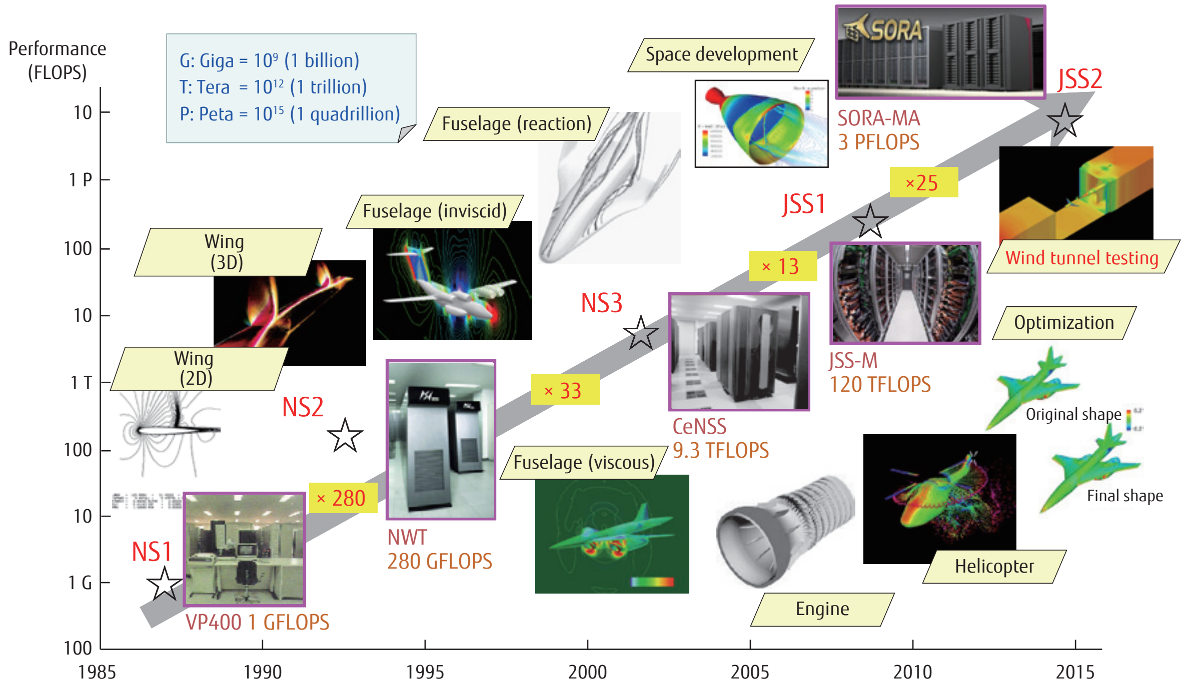


Figure 6
Supercomputer performance enhancement and development of numerical analysis technology.

enhancement of supercomputers seems to stagnate as the limitation of semiconductor process and increasing power consumption pose difficulties, new technologies such as 3D mounting and liquid cooling are being developed so that the spiral structure of performance enhancement and application development is expected to continue for a while.

Turning to what lies ahead of the numerical wind tunnel, that is, the applications of the future, the question is the direction to head in for its future development.

Supposing that the integration of numerical analysis and wind tunnel testing is materializing in the form of hybrid and numerical wind tunnels, the next step would be the flight test. A flight test is conducted in the final stage of aircraft development. Here, the purposes are to verify the performance of the developed aircraft, to obtain authorization and to address errors and defects. Similar to the approach to a numerical wind tunnel, some people attempt to employ numerical analysis to replace the flight test. This idea is called a "digital flight." The aircraft in the flight test is, unlike in a wind tunnel, exposed to real atmospheric conditions, such as humidity and turbulence. It is not easy to capture the actual conditions of the atmosphere and the aircraft while it is in the air. While JAXA has already started collecting data using its research aircraft Hisho,[23)] there is still some time before a digital flight can be put to a practical use. JAXA elsewhere implements a new concept, the integrated simulation platform, in an attempt to create new values by combining the numerical analysis with other facilities as well as with wind tunnels. This initiative is backed by the recent development of new technologies such as the Internet of Things (IoT) and artificial intelligence (AI). Ideas are being explored to propose one-stop solutions and new ways of facility deployment by integrating existing infrastructure technologies/achievements with these new technologies.

6. Conclusion

This article described the concept and historical background of the numerical wind tunnel, and explained its present development and challenges. It also stated its future prospects. It is clear that the most significant factor was the enhancement of computational performance that made it possible to improve the data productivity of the numerical wind tunnel to that of wind tunnel testing. However, the capability of computational performance does not necessarily translate into utility. In order for it to be useful, efforts must be made for the perpetual improvement of software, quantification and reduction of uncertainty, accurate understanding of needs and usability enhancement. This is a time-consuming and effort-intensive endeavor. This article may have served to give insight into the reality that the process of developing cutting-edge (unprecedented) supercomputer applications and bringing them to practical use requires considerable time. In other words, this is exactly what we mean by the evolution of supercomputing.

While this article addressed numerical analysis in the context of a numerical wind tunnel as an alternative to wind tunnel testing, we are of the opinion that wind tunnel testing will not be made obsolete in the foreseeable future. On the contrary, we expect that it will become more important in terms of aspects hitherto unrecognized and where it finds more use as numerical analysis continues to develop. One day, numerical analysis will truly surpass wind tunnel testing in data productivity. However, as we stated in the passages about the NS1, we need to keep the numerical analysis under constant check regarding its reliability and quantitativeness. Because numerical analysis needs to employ various models (turbulence, combustion, wall, etc.), precise experiments and tests are indispensable to verify these models and to develop new ones. Computation alone is not sufficient to create new models. Then, we must bear in mind that, in this context, the most important player is not analysis or testing, but our insight or intuition.

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